Thermal buckling behaviour of degraded railway tracks

Ngamkhanong, Chayut; Kaewunruen, Sakdirat; Baniotopoulos, Charalampos

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Chayut Ngamkhanong[1,2][0000-0003-1321-9952], Sakdirat Kaewunruen[1,2][0000-0003-2153-3538] and Charalampos Baniotopoulos[1]

[1] 1Department of Civil Engineering, School of Engineering, University of Birmingham, Birmingham B15 2TT, United Kingdom

[2] Birmingham Centre for Railway Research and Education, School of Engineering, University of Birmingham, Birmingham B15 2TT, United Kingdom

cxn649@bham.ac.uk

Abstract. At present, railway track buckling, caused by extreme heat, is a serious issue that causes a huge loss of assets in railway systems. The increase in rail temperature can induce a compression force in the continuous welded rail (CWR). It is important that a greater expansion in CWR can induce a higher risk of track buckling, especially when track defects exist. It is important to ensure the lateral stability of railway track in order to tackle the extreme heat. However, in fact, railway track can be progressively degraded over time resulting in poorer track stability. This may reduce the lateral resistance of railway tracks resulting in increasing the risk of track buckling. In this study, 3D finite element models are first developed to investigate the buckling behaviour of ballasted railway tracks considering the large lateral track misalignment and component deteriorations. This study also proposes the spot replacement method at the certain spans to be fully restrained laterally in order to improve buckling strength. The new findings firstly highlight the buckling phenomena of degraded railway tracks. The results suggest the proper spans that need to be fully restrained in the lateral plane. This method provides a cost-effective solution to improve track buckling strength as the number of spans has been optimised in this analysis. The insight derived from this study will underpin the lifecycle design, maintenance, and construction strategies related to the spot replacement sleepers in degraded railway track systems.

Keywords: Railway ballasted track, Track buckling, Extreme heat, Vulnerability, Critical infrastructure

1 Introduction

At present, railway track buckling, cause by extreme heat, is one of the serious concerns in the railway system [1-4]. Railway infrastructure developments associated with adaptation to future climate and heatwave are expected [5-8]. Note that high temperature can possibly induce rail buckling, catenary dilatation, signalling and the heating of rolling stock components [4,9-11]. As for railway tracks, the summer heat can significantly increase the rail temperature and cause the rail to expand, causing high axial compression force in continuous welded rail (CWR). Despite CWR has a lower maintenance cost and provides a smooth ride, it still suffers from drawbacks as the track tends to be buckled easily when the rail temperature reaches a certain limit [12-15]. Based on the evidences [16-19], it is important to note that track buckling is a major cause of train derailment and causes a huge loss of assets passenger lives. Note that track buckling around the world usually occurs in conventional railway ballasted tracks due to the poor track conditions and lateral misalignment in the rails. Track buckling analysis has been widely performed considering sensitivity analysis of major parameters influencing track buckling [20-23]. Previous studies show that lateral resistance plays the major role in buckling strength and prevention. Note that concrete, which is the most widely used construction materials, is increasingly adopted as sleeper in railway system since it can provide durability, resilience, low maintenance requirements and energy efficiency [24-29]. The lateral resistance values, that can be used properly in buckling analysis, should be obtained from Single Sleeper (Tie) Push Test (STPT) [30,31]. This method provides the ballast-sleeper contact force encountering sleeper movement which can be represented as a track lateral resistance. It is important to note that concrete sleepers usually provide higher resistance than timber sleepers because of their higher density and dimensions [23,32]. The lateral force-displacement obtained from STPT can be used as an input for lateral spring element connected to sleeper ends for buckling analysis.

In fact, railway track is progressively degraded with usage making the improvement of ballasted track necessary. Most importantly, a lack of ballast support can significantly reduce the strength of railway tracks [33-35]. For instance, in a track with poor condition, large voids and gaps can easily be observed between sleepers and the ballast, usually caused by the wet track beds (highly moist ground) from natural water springs or poor drainage. The strength and drainage aspects of ballasted tracks are compromised due to the increasing level of ballast fouling [36]. It is also noted that ballast breakage, due to impact loads [37,38], is a cause of ballast fouling leading to the loss of ballast support condition. This may lead to larger particle movement resulting in more severe loss of support conditions. Hence, fouling conditions and degraded ballast decrease lateral resistance of ballasted track. The previous study presented the influences of ballast degradation on ballasted track resistance considering coal dust as a fouling agent [39]. The lateral resistance of railway tracks under ballast fouling conditions have been previously investigated using Discrete Element Modelling (DEM) simulations [40]. It is found that lateral resistance is progressively reduced when the ballast is progressively degraded. This study adopts the lateral resistance based on realistic behaviour of degraded ballast to the lateral spring to represent the sleeper-ballast lateral resistance to quantify the buckling phenomenon of ballasted tracks. This method has been previously used once considering the ballast layer geometries [41].

The advanced three-dimensional Finite Element Modelling (FEM) of ballasted railway tracks subjected to extreme temperature is presented using LS-DYNA and analysed via nonlinear analysis. The clean and fouled ballast condition are taken into account. This paper investigates the buckling phenomena based on the assumptions that ballast fouling is accumulated and formed from the ballast base and built up to the top layer. The degradation of railway track also includes lateral misalignment of tracks. The effects of unconstrained length representing the area of degraded ballast in the longitudinal direction are considered. This paper thus provides the buckling temperature and allowable temperature of railway tracks under different ballast conditions. The insights will help track engineers to improve track buckling prevention methods for conventional ballasted tracks.

2 Railway Track Buckling

In general, if the rail temperature is higher than the neutral temperature, the compression axial force in the rails builds up. The rails may buckle when the compression force reaches its limit or the buckling resistance. The relationship between the rail temperature and the lateral displacement of rails can be typically plotted as shown in **Fig. 1**. It can be seen that there are two types of buckling failure modes: sudden buckling and progressive buckling, depending on the failure mechanism and buckling paths. In the pre-buckling stage, the rails are exposed to a higher temperature than the neutral temperature and the axial force is linearly increased. As for the sudden buckling mode (also called 'snap-through'), the track buckles explosively with no external energy after reaching its maximum temperature (upper critical temperature, T_{max}) and becomes unstable in its post-buckling stages. T_{min} represents the lower bound, which can buckle the track if sufficient energy is supplied. It can also be defined as a safe temperature, as the track cannot buckle if it experiences a temperature below this temperature. Moreover, progressive buckling can occur when T_{min} cannot be differentiated from T_{max}, as the peak cannot be seen clearly. In this case, the track's lateral displacement gradually increases after buckling, and the critical temperature is defined as T_P. It is recommended to evaluate the corresponding buckling axial force as an indicator in case of progressive buckling as the buckling temperature cannot be detected clearly.

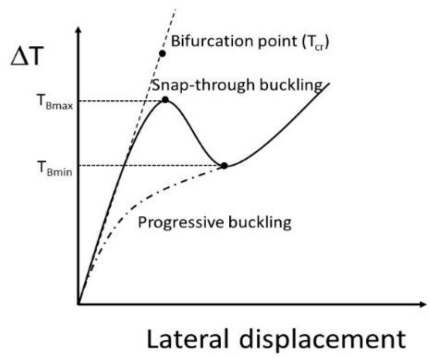
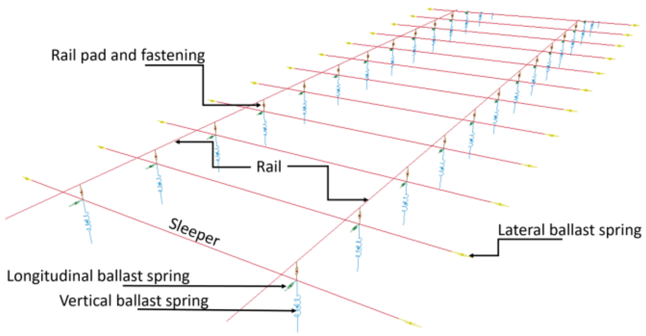


Fig. 1. Buckling path.

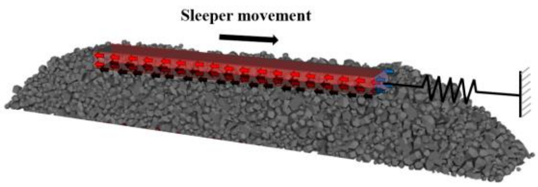
3 Methodology

Ballasted railway tracks with the standard gauge, that have been previously built and validated in LS-DYNA, are used in this study, as shown in **Fig. 2**a. Steel rails UIC60 and sleepers are modelled using beam elements, which take into account shear and flexural deformations. Rails and sleepers are built using SECTION_BEAM and MAT_ELASTIC. The rail pads and fasteners are modelled as a series of spring elements using SECTION_DISCRETE and SPRING_ELASTIC in the connections between sleepers and rails. At rail seat, rail pad and fastener, three translational springs to represent pad stiffness in three directions and one rotational spring to represent the fastener resistance, are applied. For ballast, the tensionless support spring should be considered and connected to each sleeper ends instead of the normal spring since it allows the beam to lift and move over the support while the tensile support is neglected. This presents realistic behaviour of the ballast. The lateral spring representing the ballast layer confronting sleeper movement is shown in **Fig. 2**b. Note that the lateral spring properties for clean and fouled conditions have been derived previously [40].

As for the boundary conditions, the fully fixed supports are applied to the end nodes of the rails. Note that, normally after buckling, tracks can be divided into two regions: buckled and adjoining regions. The roller supports are applied longitudinally on the rails to generate a stiff track area representing adjoining regions so that the rails are constrained and not allowed to move transversally. Hence, the unconstrained length is presented as a weaker track and thus the buckled region is expected in this area. In this study, the track is originally made of 60 m in length with buckled regions of 30m as track buckling length is always roughly from a very short to 30m [42]. It is noted that the unconstrained length of 30m is a control case and chosen for nonlinear analysis. Then, the unconstrained length is reduced to study its effects on improving buckling strength.



a)



b)

Fig. 2. a) Simplified finite element modelling of ballasted railway track b) Lateral ballast spring representing sleeper-ballast lateral resistance [40].

The properties and dimensions of conventional railway tracks are presented in **Table 1**. while the lateral spring properties are derived in accordance with the lateral force-displacement of sleepers obtained in the past study. It is noted that the properties are considered on the basis of the nominal values used widely in normal track conditions. It is important to note that the lateral force-displacement curves are linked to the lateral spring mapping of ballast performances in lateral plane.

In the nonlinear buckling analysis, the solution method uses the nonlinear approach with the BGFS quasi newton algorithm in LS-DYNA. This iterative method is used for solving unconstrained nonlinear optimisation problems. A temperature of 200 °C is applied to the system using the keyword LOAD_THERMAL_LOAD_CURVE in LS-DYNA. The thermal expansion is applied to the rails using the keyword MAT_ADD_THERMAL_EXPANSION.

Table 1. Material properties.

Parameter list	Characteristic value	Unit
Rail (UIC60)		
Modulus	2×10^5	MPa
Density	7850	kg/m^3
Poisson's ratio	0.25	
Thermal expansion	1.17×10^{-5}	1/°C
Mono-block concrete sleeper [260x235x2600mm]		
Modulus	3.75×10^4	MPa
Shear modulus	1.09×10^4	MPa
Density	2740	kg/m^3
Poisson's ratio	0.2	
Torsional fastening resistance	75	kNm/rad

According to previous STPT simulations on ballast lateral resistance, load-displacement curves have been obtained. It should be noted that the original curves can be fitted well with bilinear curves as presented in **Fig. 3** for concrete sleepers placed on clean and fouled ballast layers. The displacement limit, which is the inflection of stiffness, is set as 0.5mm as it can be clearly detected as a yield point. The original curves are fitted with bilinear curves using the linear polynomial fit method.

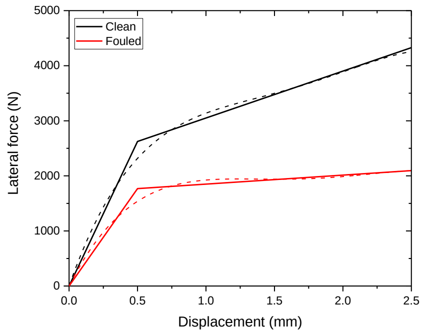


Fig. 3. Lateral resistance of ballasted railway track.

4 Results and Discussions

Fig. 4 illustrates the rail axial force against the increase in rail temperature of railway tracks with clean and fouled ballast considering its unconstrained length 30 m. The axial forces of rails in railway tracks with the misalignment amplitudes from 8 mm to 32 mm are compared. The maximum axial force represents the buckling force which can be used to evaluate the corresponding buckling temperature. As for track with 30 m unconstrained length, the buckling failure mode is likely to be snap-through buckling mode. When railway tracks have bigger size of misalignment (24 mm and 32 mm), buckling failure mode is still snap-through but likely to be more progressive mode when the misalignment increases in size.

It should be noted that, rail axial force drops immediately after buckling and track enters the post-buckling stage as presented. In post-buckling stages, there is a lateral excitation in the beginning and then track becomes stable showing the progressive reduction trend of axial force. When projecting a trend line of axial force in post-buckling toward the pre-buckling stage, the line intersects the axial force in the pre-buckling stage. The intersection point represents the minimum axial force that can buckle the track. The projection of this point to the x axis represents the minimum temperature over neutral or safe temperature. In this case, it is found that rail axial forces for all cases are likely to be the same within the similar ballast condition once the tracks become stable after buckling. It means that the safe temperature is not affected by initial track misalignment amplitudes.

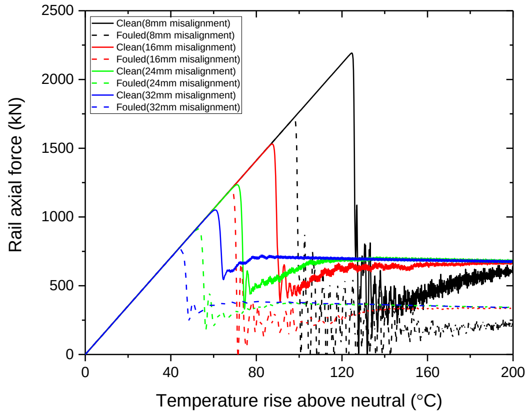


Fig. 4. Rail axial force due to temperature change.

The buckling and safe temperatures over neutral for railway tracks are presented in **Fig. 5**. It is clearly seen that fouled ballast can significantly reduce the buckling and safe temperatures, which obviously increases the likelihood of track buckling. Moreover, high misalignment coupled with fouled ballast that occurs in the larger area can greatly reduce the buckling temperature leading to more risk to buckling. For tracks with fouled ballast layer, the safe temperature can be lower than 30 °C which can be usually experienced in summer. For this reason, train speed on degraded railway tracks should be limited in summer to avoid the additional energy that can increase the risk of track buckling.

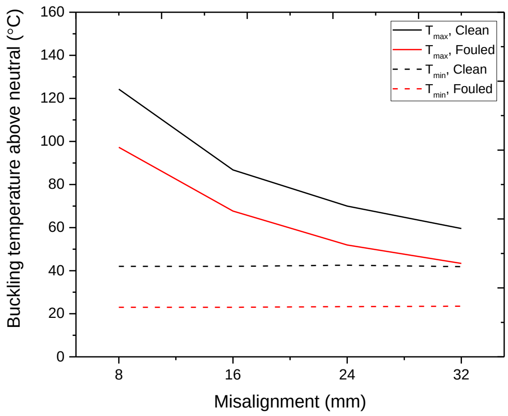


Fig. 5. Buckling and safe temperatures.

Considering the unconstrained length, the buckling temperatures are compared. It is clear that the buckling temperature of tracks with unconstrained length of 6m and 12m under the same ballast condition are clearly distinct from others, as seen in **Fig. 6**. While the railway tracks are generally buckled within the same ranges when the unconstrained length is larger than 18 m. The results suggest that decreasing unconstrained length to 12m can obviously improve track buckling strength resulting in much higher buckling temperature

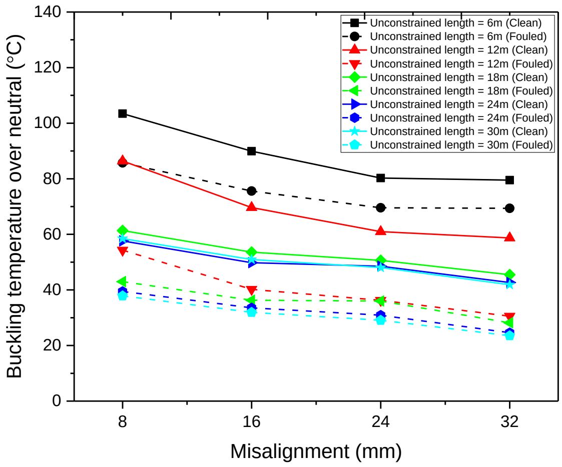


Fig. 6. Buckling temperature over neutral considering unconstrained length and track misalignment.

5 Conclusions

This study presents the 3D finite element models to investigate the buckling behaviour of ballasted railway tracks considering ballast degradation. The lateral force against sleeper displacement curves obtained from previous simplified DEM results are used as a lateral resistance for ballast lateral spring in track buckling modelling. The key findings are revealed as follows.

- In general, snap-through buckling normally occurs especially for the ballasted track with new clean ballast. However, in the same track, buckling failure mode is likely to be shifted from snap-through to progressive buckling when the track is degraded including poorer track lateral misalignment and ballast fouling conditions. It can be obviously seen that the different between buckling temperature and safe temperature is much smaller when the buckling failure mechanism is shifted to progressive buckling mode.
- The risk of track buckling is far greater for railway tracks with fouled ballast conditions. This shows that buckling strength of ballast track is reduced over time due to the progressive degradation of ballast leading to prone to

buckling. Note that ballast fouling condition coupled with larger track misalignment can significantly reduce the allowable temperature.

- Reducing the unconstrained length to 12 m or 20 spans can potentially reduce the risk of track buckling for all ballast conditions. This outcome will help optimise the proper cost-effective strengthening method for buckling strength by restraining the sleeper at optimised spans.

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